Electrical polarization of nuclear spins in a breakdown regime of quantum Hall effect

M. Kawamura,* H. Takahashi, K. Sugihara, S. Masubuchi, K. Hamaya, and T. Machida†
Institute of Industrial Science, University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
(Dated: February 3, 2008)

We have developed a method for electrical polarization of nuclear spins in quantum Hall systems. In a breakdown regime of odd-integer quantum Hall effect (QHE), excitation of electrons to the upper Landau subband with opposite spin polarity dynamically polarizes nuclear spins through the hyperfine interaction. The polarized nuclear spins in turn accelerate the QHE breakdown, leading to hysteretic voltage-current characteristics of the quantum Hall conductor.

PACS numbers: 74.43.-f

Control of nuclear spins in semiconductor has attracted considerable interests because nuclear spin is one of the most promising elements for implementation of quantum bit.[1] Several techniques have been developed for optical[2,3] and electrical[4,5,6,7,8,9,10,11,12] control of nuclear spins. In quantum Hall (QH) systems, two kinds of approaches for all-electrical manipulation of nuclear spins have been demonstrated.[4,5,6,7,8,9,10,11] One technique utilized spin-flip scattering of electrons between spin-resolved QH edge channels.[4,5,6,7,8] The flip of electron spin $\boldsymbol{S}$ flops nuclear spin $\boldsymbol{I}$ through the hyperfine interaction, $\mathcal{H}_{\rm hyp} = A\boldsymbol{I}\cdot\boldsymbol{S} = A(I^+S^- + I^-S^+)/2 + AI_zS_z$, where A is the hyperfine constant. The nuclear spin polarization was detected by measuring Hall resistance. Another technique utilized domain structure with different spin configurations in fractional QH systems.[9,10,11] The spin-flip process of electrons traveling across the domain boundary flops nuclear spins through the hyperfine interaction.

Nuclear spin polarization has been also utilized as a probe to investigate electron spin properties in two-dimensional electron systems (2DESs), which had not been accessed by standard magnetotransport measurements. Indeed, the excitation of spin texture in a QH system[10] and the low frequency spin fluctuations in closely separated bilayer 2DESs[13] were observed using resistively detected nuclear spin relaxation. Thus, development of a method for electrical polarization and detection of nuclear spins will open a way to find spin-dependent phenomena in QH systems.

In this letter, we demonstrate a method for electrical polarization of nuclear spins using the breakdown of integer quantum Hall effect (QHE). In a breakdown regime of odd-integer QHE, electrons are excited to the upper Landau subband with opposite spin polarity. The spin-flip process of electrons dynamically polarizes nuclear spins through the hyperfine interaction. The polarized nuclear spins in turn reduce the spin-splitting energy of Landau subbands, accelerating the QHE breakdown. The voltage-current characteristic curve is shifted due to the dynamical nuclear polarization (DNP). The relevance of the DNP to the shift is confirmed by the detection of nuclear magnetic resonance (NMR).

We propose a concept for electrical polarization of nuclear spins in an odd-integer QHE regime, where the Fermi energy resides in the energy gap of spin-split Landau subbands. In this condition, the lower Landau subband (N, $\uparrow$) is fully occupied with up-spin electrons, while the higher down-spin subband (N, $\downarrow$) is empty. When a current is transmitted through the conductor, the Landau subbands are tilted due to the Hall electric field as schematically shown in Fig. 1(a). When the current is increased above a critical current I_c, electrons in the lower Landau subband (up-spin) are excited to the higher empty subband (down-spin), giving rise to an abrupt increase of longitudinal voltage V_{xx}. This phenomenon is referred to as the QHE breakdown.[14,15] Possible excitation processes of electrons include the Zener-type tunneling (ZT)[16] and the impact excitation (IE)[17] [Fig. 1(a)]. Though the mechanism of the QHE breakdown has been still under debate, it is obvious that the excitation processes are accompanied by up-to-down spin flips of electrons. Accordingly, we expect that the QHE breakdown can be utilized to polarize nuclear spins, i.e. the up-to-down spin flips of electrons dynamically polarize the nuclear spins along the external magnetic field B ($\langle I_z\rangle > 0$) through the counter spin flops of nuclear spins

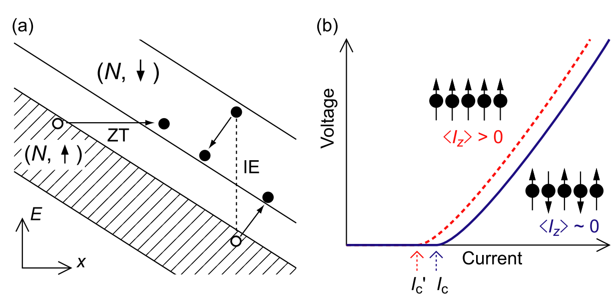

FIG. 1: (a) A schematic diagram of spin-split Landau subbands in a breakdown regime of an odd-integer QHE. Electrons are excited to the upper subband through the Zener-type tunneling (ZT)[16] and the impact excitation (IE).[17] In the IE process, electrons in the higher subband are accelerated by the Hall electric field to excite another electron in the lower subband through the electron-electron scattering. (b) A schematic representation of the expected V_{xx}-I curves at $\langle I_z\rangle \sim 0$ (solid) and $\langle I_z\rangle > 0$ (dashed).

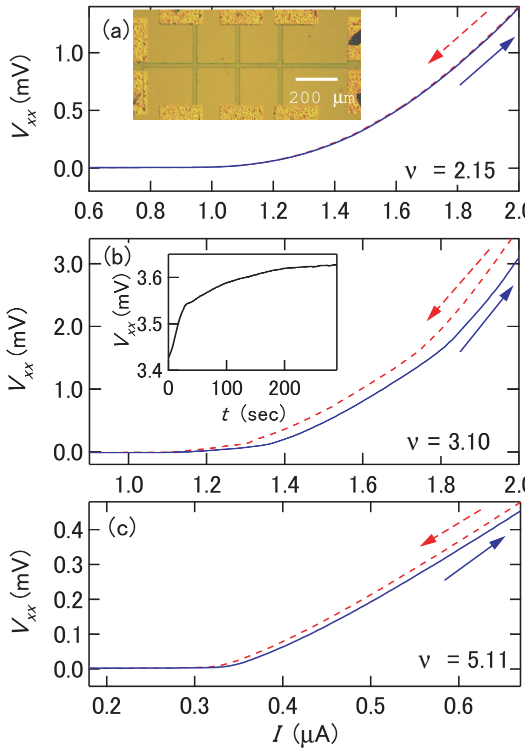

FIG. 2: V_{xx}-I curves taken by sweeping current in positive (solid) and negative (dashed) directions at (a) ν = 2.15 (B = 5.15 T), (b) ν = 3.10 (B = 3.58 T), and (c) ν = 5.11 (B = 2.17 T). Inset of (a): A micrograph of the Hall-bar device. Inset of (b): Time evolution of V_{xx} after the current is changed from I = 0.0 μA to 2.0 μA at t = 0.

in the hyperfine interaction[18].

When the nuclear spins are polarized in the QHE breakdown regime, the polarized nuclear spins ($\langle I_z \rangle > 0$) reduce the spin-splitting energy $E_{\rm S} = |g|\mu_{\rm B}B - A\langle I_z\rangle$, where g is the g factor of electrons (= -0.44 in GaAs) and $\mu_{\rm B}$ is the Bohr magneton. Since the odd-integer QHE is stabilized by $E_{\rm S}$, the reduction of $E_{\rm S}$ is expected to accelerate the QHE breakdown, leading to the shift of voltage-current (V_{xx}-I) curves toward the smaller current side as shown in Fig. 1(b). Thus, the V_{xx}-I curve is expected to show hysteresis depending on the sweep direction of the current. Nachtwei *et al.* observed hysteretic V_{xx}-I curves in InGaAs/InAlAs systems, but they excluded the relevance of nuclear spins and interpreted the hysteresis in terms of quantum Hall ferromagnet.[19] Song and Omling also reported hysteretic magnetotransport in the regime close to the QHE breakdown.[20] They found an unexpected huge differential resistance peak with a very slow relaxation time and suggested the influence of nuclear spins on it. However, the relationship between the nuclear spins and the QHE breakdown has been unclear.

A Hall-bar device with a channel width of 20 μm was fabricated by photolithography from a wafer of GaAs/AlGaAs single heterostructure[21][inset of Fig. 2(a)]. The mobility and sheet carrier density of

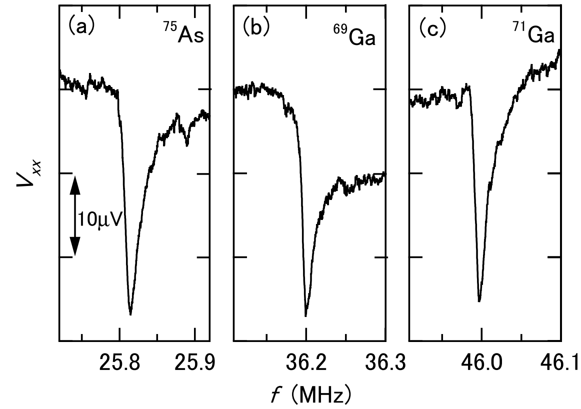

FIG. 3: NMR spectra for (a)^{75}As, (b)^{69}Ga, and (c)^{71}Ga detected by measuring V_{xx}. The sweep rate of rf magnetic fields is 13 kHz/min.

the 2DES are μ = 60 m^2/Vs and n = 2.7 $\times 10^{15}$ m^{-2}, respectively. The longitudinal voltage V_{xx} was measured by a standard dc four-terminal method in a dilution refrigerator with a base temperature of 20 mK. A single-turn coil around the device was used to irradiate radio-frequency (rf) magnetic fields.

Voltage-current curves in QHE regimes were taken by sweeping the current between -2.5 μA and 2.5 μA at various Landau-subband filling factors ν. Figures 2(a)-2(c) show the V_{xx}-I curves in QHE regimes at ν = 2.15 (B = 5.15 T), ν = 3.10 (B = 3.58 T), and ν = 5.11 (B = 2.17 T). The solid and dashed curves are respectively obtained by sweeping the current at a rate of 0.012 μA/s in positive and negative directions. The value of V_{xx} starts to increase at I = 1.0 μA, 1.1 μA, and 0.33 μA for ν = 2.15, 3.10, and 5.11, respectively. At ν = 3.10 and 5.11 [Figs. 2(b) and 2(c)], the shift of the down-sweep curves toward the smaller current side is observed, while no shift is found at ν = 2.15 [Fig. 2(a)]. The observed shift of the V_{xx}-I curves is consistent with our expectation [Fig. 1(b)].

The inset of Fig. 2(b) shows time evolution of V_{xx} at ν = 3.10 after the current is changed from I = 0.0 μA to 2.0 μA. The value of V_{xx} increases slowly with a relaxation time over 300 s,[22] which is a typical time scale for the nuclear spin relaxation.[4,5,6,7,8,9,10,11] The increase in V_{xx} indicates the acceleration of the QHE breakdown due to the reduction of the spin-splitting energy $E_{\rm S}$.

The relevance of DNP to the shift of the V_{xx}-I curves is unambiguously confirmed by the NMR measurements described below. A rf magnetic field parallel to the 2DES is applied after V_{xx} is completely saturated at I = 2.0 μA. The value of V_{xx} decreases at the NMR frequencies of ^{75}As, ^{69}Ga, and ^{71}Ga as shown in Figs. 3(a)-3(c). The detection of NMR shows that the shift of the V_{xx}-I curves are caused by the DNP and that the nuclear spins are polarized in the QHE breakdown regime.

The shift of the V_{xx}-I curves is prominent in the odd-integer QHE plateaus of ν = 3 and 5 [Figs. 2(b) and

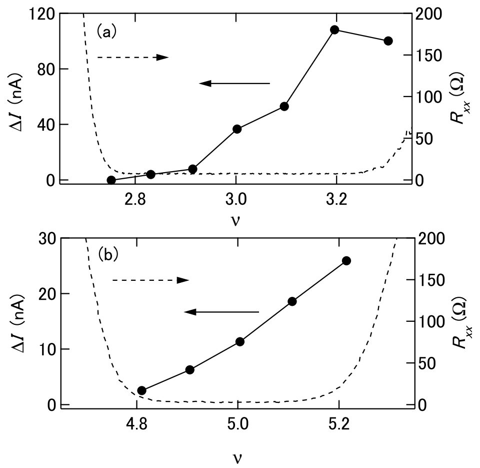

FIG. 4: Shift of V_{xx}-I curves between up- and down-sweeps at $V_{xx} = 2$ mV as a function of the Landau-subband filling factor in the QHE plateau regions of (a) $\nu = 3$ and (b) $\nu = 5$. The longitudinal resistance R_{xx} is plotted together by the dashed curves.

2(c)], while it is almost absent in the even-integer QHE plateaus of $\nu = 2$, 4, and 6 [Fig. 2(a)], where the cyclotron energy $\hbar\omega_c$ ($\gg g\mu_B B$) is the relevant energy gap for the excitation process in the QHE breakdown. Within the QHE plateaus of $\nu = 3$ and 5, the shift of the V_{xx}-I curves (ΔI) at $V_{xx} = 2$ mV increases monotonically with increasing the filling factor of Landau subbands as shown in Figs. 4(a) and 4(b), i.e. the hysteresis is more prominent when the Fermi energy locates closer to the upper Landau subband.

In a breakdown regime of QHE ($I > I_c$), current flows mainly in the inner bulk region of the 2DES. However, in the Hall-bar geometry, edge channel transport may contribute to the DNP. To know whether the bulk region is polarized, we studied another device with Corbino geometry, where the edge-channel transport is completely absent. We observed the similar shift of V_{xx}-I curves in breakdown regimes of odd-integer QHE ($\nu = 1$, 3, and 5) and detected the NMR signals. These results definitely show that the nuclear spins in the bulk region of the 2DES are polarized and detected in this technique[23]. Details of the Corbino geometry experiment will be described elsewhere.

To summarize, we have demonstrated a method for electrical polarization of nuclear spins in the inner bulk region of a quantum Hall conductor. In a breakdown regime of odd-integer QHE, the excitation of electrons to the upper Landau subband with opposite spin polarity polarizes nuclear spins through the hyperfine interaction. The dynamic nuclear polarization in turn reduces the spin-splitting energy of Landau subbands, accelerating the QHE breakdown.

This work is supported by PRESTO, JST Agency, the Grant-in-Aid from MEXT (No. 17244120), and the Special Coordination Funds for Promoting Science and Technology.

---

* Electronic address: minoru@iis.u-tokyo.ac.jp
† Electronic address: tmachida@iis.u-tokyo.ac.jp

1 B. E. Kane, Nature (London) **393**, 133 (1998).
2 G. Salis, D. T. Fuchs, J. M. Kikkawa, D. D. Awshalom, Y. Ohno, and H. Ohno, Phys. Rev. Lett. **86**, 2677 (2001).
3 H. Sanada, Y. Kondo, S. Matsuzaka, K. Morita, C. Y. Hu, Y. Ohno, and H. Ohno, Phys. Rev. Lett. **96**, 067602 (2006).
4 B. E. Kane, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **46**, 7264 (1992).
5 K. R. Wald, L. P. Kouwenhoven, P. L. McEuen, N. C. van der Vaart, and C. T. Foxon, Phys. Rev. Lett. **73**, 1011 (1994).
6 T. Machida, S. Ishizuka, T. Yamazaki, S. Komiyama, K. Muraki, and Y. Hirayama, Phys. Rev. B **65**, 233304 (2002).
7 T. Machida, T. Yamazaki, and S. Komiyama, Appl. Phys. Lett. **80**, 4178 (2002).
8 T. Machida, T. Yamazaki, K. Ikushima, and S. Komiyama, Appl. Phys. Lett. **82**, 409 (2003).
9 S. Kronmüller, W. Dietsche, K. von Klitzing, G. Denninger, W. Wegscheider, and M. Bichler, Phys. Rev. Lett. **82**, 4070 (1999).
10 K. Hashimoto, K. Muraki, T. Saku, and Y. Hirayama, Phys. Rev. Lett. **88**, 176601 (2002).
11 G. Yusa, K. Muraki, K. Takashina, K. Hashimoto, and Y. Hirayama, Nature (London) **434**, 1001 (2005).
12 K. Ono and S. Tarucha, Phys. Rev. Lett. **92**, 256803 (2004).
13 N. Kumada, K. Muraki, and Y. Hirayama, Science **313**, 329 (2006).
14 G. Ebert, K. von Klitzing, K. Ploog, and G. Weimann, J. Phys. C **16**, 5441 (1983).
15 M. E. Cage, R. F. Dziuba, B. F. Field, E. R. Williams, S. M. Girvin, A. C. Gossard, D. C. Tsui, and R. J. Wagner, Phys. Rev. Lett. **51**, 1374 (1983).
16 L. Eaves and F. W. Sheard, Semicond. Sci. Technol. **1**, 346 (1986).
17 S. Komiyama and Y. Kawaguchi, Phys. Rev. B **61**, 2014 (2000).
18 Energy difference of electrons between the initial and final states in the ZT and IE excitations can be as small as the nuclear spin excitation energy.
19 G. Nachtwei, A. Manolescu, N. Nestle, and H. Künzel, Phys. Rev. B **63**, 045306 (2000).
20 A. M. Song and P. Omling, Phys. Rev. Lett. **84**, 3145 (2000).
21 In the heterostructure used in the present study, the value of I_c is proportional to the width of conduction channel.
22 When a current with opposite polarity $I = -2.0$ μA is applied, $|V_{xx}|$ increases slowly as well.
23 Because the QHE breakdown develops along the current direction, the DNP may have spatial distribution along the channel.